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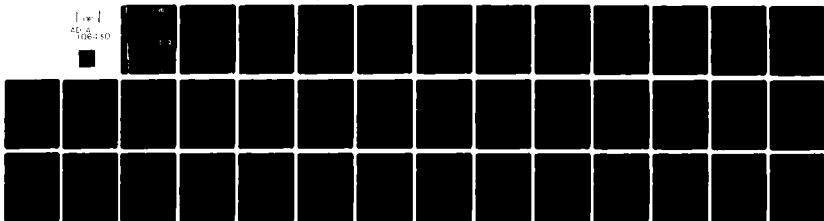
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# Kafjord, Norway Transmission Line VLF Antenna Tests, 1979-1980

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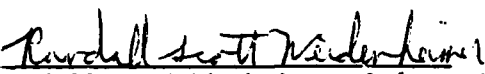
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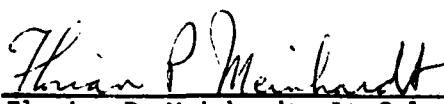
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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The 100-kW Transportable Very-Low-Frequency (TVLF) system was used at Kaffjord, Norway, for transmissions to the SCATHA and GEOS spacecraft. A 22-kV 14-km long transmission line was used as an antenna. Modifications were made in the line to reduce telephone interference, and components were designed and installed to reduce the resonant frequency and increase the antenna current. Final practical operating current was 40 amperes at 1280 Hz, which resulted in power dissipation of 72 kW and an estimated radiated power of 29 watts.		

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## PREFACE

Dr. Harry Koons of The Aerospace Corporation has been the principal investigator on the TVLF programs to transmit to satellites for three campaigns in Norway, and in Alaska and New Zealand. His patient support of the measurement and construction tasks has allowed the improvements described herein.

The initial impetus to use the TVLF transmitter in Scandinavia was provided by Dr. Arne Pedersen of ESTEC. The Space Activity Division of the Royal Norwegian Council for Scientific and Industrial Research (NTNF) was particularly helpful with numerous negotiations and arrangements with Norwegian agencies. We are especially indebted to Prof. Jan A. Holtet of the University of Oslo who devoted many months helping in the field, and working with the local and national agencies to insure success in the transmissions, to Prof. Les Wooliscroft, University of Sheffield, who was able to inspire a number of agencies to help us financially, and in addition, made the ground calibration measurements for the 1980 campaign and to R. G. Robbins, R. L. Walter, and J. Døhl who worked hard to overcome all of the equipment failures and keep the transmitter on the air. We wish to thank Prof. M. Garnier, G. Girolomi and J. Conrad, University of Paris, who made measurements and transmissions which were helpful in designing components for the larger transmitter, and demonstrated a transmission line configuration that would not cause telephone interference.

This work was supported in part by the National Science Foundation under Grant ATM77-19361 and in part by the U. S. Air Force Space Division under Contract F04701-80-C-0081.

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## Background

Very low frequency (VLF) transmissions from the surface of the earth to the European Space Agency satellite GEOS and the U. S. Air Force satellite SCATHA have been used to study wave-particle interactions in the outer magnetosphere. The longitudinal positioning of GEOS and the orbit of SCATHA made it necessary to transmit from Scandinavia.

An informal cooperative program was arranged by Aerospace personnel with the European Space Agency Personnel, and the Royal Norwegian Council for Scientific and Industrial Research (NTNF), Space Activity Division. The Aerospace Corporation supplied the 100 kW Transportable Very Low Frequency (TVLF) System supported in part by the National Science Foundation, while the Norwegians supplied power lines for antennas and made local arrangements.

VLF transmitting antennas typically have required either large, expensive, permanent structures, or temporary systems such as a tethered balloon or an airborne long wire. Norwegian scientists arranged for the use of existing electrical power transmission lines as antennas, thereby eliminating installation costs and making operation possible in weather conditions that would destroy a balloon supported antenna.

A 22 km, 60 kilovolt line was made available at Andoya, Norway. In March 1978, Professor Garnier from the University of Paris and his people attempted transmissions to GEOS using the 1 kW transmitter and the Andoya line. Use of the 60 kV Andoya line as a VLF antenna required the electrical load of the town of Andenes to be carried by an older 22 kV line. The tests of March 1978 were made on a very cold night when the electrical load was high and as a consequence the line voltage dropped approximately 20% throughout Andenes and

nearby towns.

The lowered voltage is believed to have caused some appliance damage in Andenes. No difficulties of any kind were reported related to the local telephone system. The temporary assignment of the 60 kV Andoya line to VLF applications had been arranged on an informal basis with the expectation that local residents would not experience problems. The undesirable consequences caused the NTNF personnel to be extremely reluctant to make further informal agreements to use the Andoya line as a VLF antenna.

In June of 1978 NTNF personnel informed the Aerospace personnel that the Sortland Line, a line that ran about 34 km between the towns of Strand and Konstadbøtn, Norway, was available for use as a VLF antenna. The Sortland line is a "stand-by" line, and was being kept available for use when it was necessary to service an operating line; thus it was not necessary to do any switching or otherwise cause problems with the local electrical distribution network when VLF transmissions were being made.

Two days of operation with currents of up to 60 amperes resulted in severe telephone interference and widespread complaints. The interference was attributed to the fact that the Sortland line was installed within a few hundred meters of a fjord throughout most of its length and a large number of telephone subscribers had residences between the line and the fjord.

A third line was located in a remote part of Norway, about 300 km from Tromsø near the town of Kafjord. The line was approximately 15 km long and there were a few telephone subscribers near the Kafjord end of the line. Low level tests indicated serious telephone interference in the nearby residences. Since the residences were all close to the transmitter end of the line, a test was made with the first 3.6 km of the line 'floating' above

ground with the current being inserted into the ground at the 3.6-km point. Tests with subscribers and the telephone switchboard indicated that currents considerably above 50 amperes could be used without causing interference in the telephone system.

It was assumed that the interference was caused by potential gradients associated with the "ground return" currents which cause voltage differences between the numerous grounding points of a typical telephone system.

This report describes tests and results obtained with the Kafjord line.

## The Operating Mode of Transmission Line Antennas

In the simplest configuration, a transmission line antenna can be considered a rectangular loop antenna with current going out on the transmission line wires, returning to ground at the far end, and returning in the ground back to the low potential side of the transmitter. When VLF currents travel in the ground they penetrate large distances because of the skin depth phenomenon and the low frequencies involved. Therefore in its simplest form the area of the loop antenna is given by multiplying the length of the transmission line by the skin depth at the frequency of interest.

An early concept of a transmission line antenna was the Beverage antenna which utilized a terminating resistor as a load at the far end of a long wire to avoid detuning and high voltages which could result from resonances. If the line insulators can tolerate the high voltages, more current can be obtained by operating the line at a resonant frequency, and the terminating resistor is eliminated as a source of power loss.

In the interest of safety and ease of design high-power transmitters are usually operated at high currents and relatively low voltages, which constitutes a low output impedance. A transmission line a quarter of a wavelength long with an open circuit at the far end provides a low impedance for a transmitter and is the preferred operating mode.

Our studies indicate that VLF currents in the ground encounter a resistance per unit length,  $R_e/m$ , which is independent of the earth resistivity and is only a function of frequency,  $f$ . The resistance value appears to be  $R_e/m = 10^{-6} \times f$  ohms/meter where  $f$  is the frequency in Hertz.

In addition to the resistance described above, there is an added resistance when ground stakes are used to connect the low potential side of the TVLF system to the earth. This resistance is caused by current concentrations near the stakes and is a function of earth resistance, the number of stakes used and their placement. For simplicity we assume that the ground insertion resistance is independent of frequency. Based on our measurements, the value can be as low as a few ohms or as high as 100 ohms.

An advantage of a quarter-wave open-circuit antenna is that only one connection to the earth is necessary.

In general, when a transmission line is provided the quarter wave resonance does not occur at a desired frequency. For transmissions to the SCATHA and GEOS satellites the desired frequency was about 1300 Hz, based on the expected electron gyrofrequency at the location of the spacecraft. We find the typical propagation velocity in transmission line antennas to be about 0.7 the speed of light for the lines measured in North Norway. The desired length of a transmission line for quarter wave resonance is then given by:

$$l = \frac{3 \times 10^5 \times .7}{4 \times 1300} = 40 \text{ km}$$

As a practical matter, it is difficult to arrange the use of power transmission lines because of power company constraints, and the lines that have been made available are usually shorter than 40 km. The shorter lines may be electrically lengthened by adding the proper components.

In the 1979 campaign, the Kafjord line was lengthened by adding capacitors at the far end. There were several voltage, frequency and current requirements for the capacitors, however, special units were obtained that

functioned satisfactorily. The capacitor current had to be re-inserted into earth, requiring a second grounding connection. The capacitor ground connection was made in inhospitable terrain and added considerable series resistance to the complete system.

In the 1980 campaign, a special inductor was constructed at the TVLF transmitter site and connected in series with the transmission line achieving the necessary reduction in resonant frequency with minimal increase of circuit resistance.

Details and performance results of the TVLF-antenna combination are discussed below.

#### Electrical Characteristics of the Kaffjord Line

It is desirable to determine the electrical parameters of transmission lines being considered for VLF antennas for a number of important reasons. The design of the tuning elements, if necessary, must be based upon the expected impedance of the line and the desired operating levels of voltage and current. The series resistance,  $R_s$ , determines how much antenna current can be supplied by a power amplifier with a given amount of power and a known output impedance. The characteristic impedance is related to the skin depth in the earth and estimates of this parameter allows one to determine the expected radiated power.

Figure 1 illustrates schematically three of the Kaffjord, Norway transmission-line antenna configurations. Note that in all three cases, 3.6 km of elevated line was used to transmit the power to the 10.6 km of line which was the actual antenna. Impedance measurements were made in all three configurations and estimates of inductance/meter, capacitance/meter, characteristic

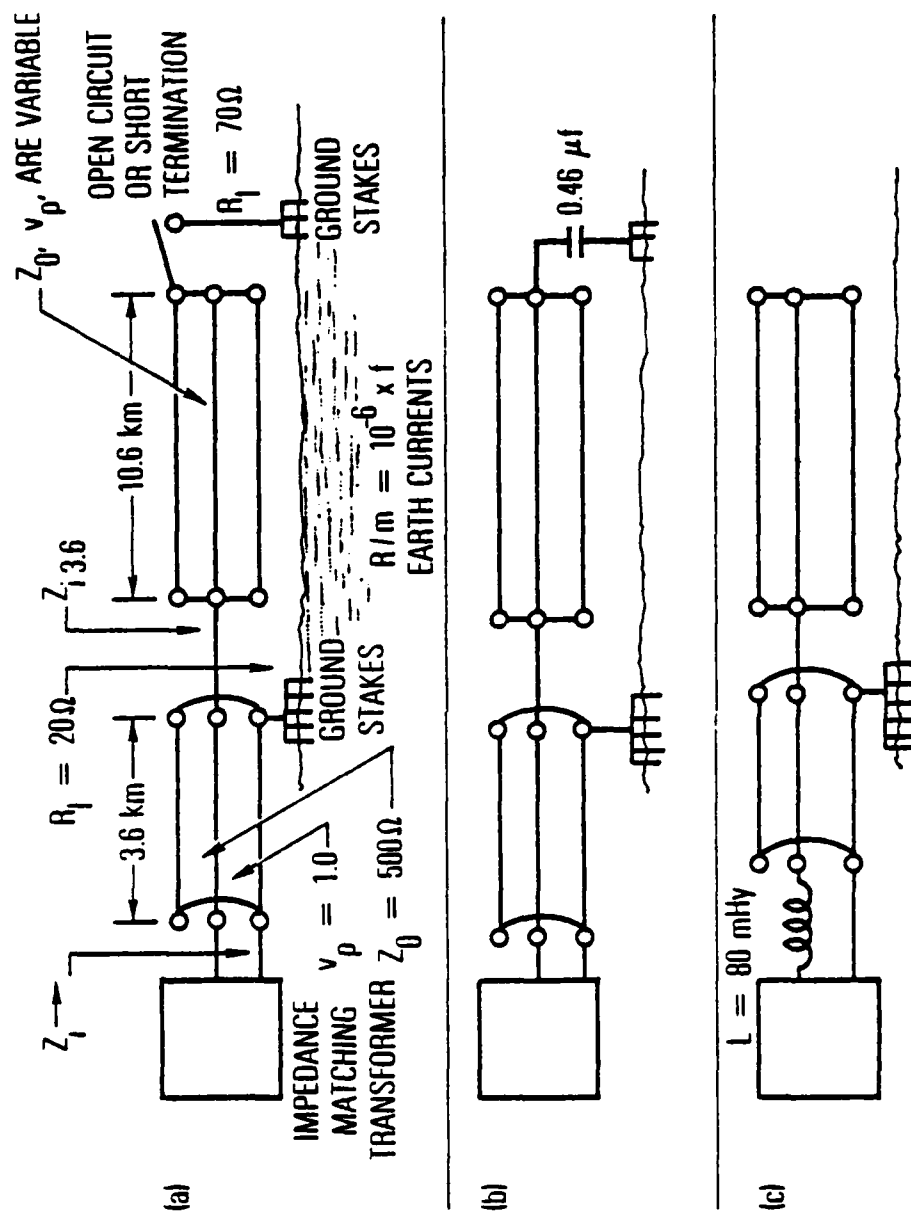


FIG. 1. Keford line; (a) Test configuration, resonant frequency = 3.8 kHz, (b) capacitive tuning, resonant frequency = 1.3 kHz, (c) inductive tuning, resonant frequency = 1.3 kHz.

impedance, velocity of propagation, skin depth in the earth, and earth resistivity were made as a function of frequency.

Impedances were measured as described by Dazey and Koons (1977). The measurement technique provides the modulus of the impedance, rather than the reactive and resistive terms, although at points of inflection in the curves, one can assume the impedance is purely resistive. The skin depth varies significantly with frequency and this causes significant changes in the characteristic impedance and the velocity of propagation. Since the total line included a 3.6-km portion with fixed impedances it appeared that there were too many variables to achieve an analytical solution, so trial-and-error curve fitting methods were adopted.

The short circuit and open circuit impedance values of the Kafjord line are shown in Figures 2 and 3. The analytical expressions for the short circuit and open circuit transmission lines are shown below:

The general transmission line formula is:

$$Z_i = \frac{Z_o (Z_L \cosh \theta + Z_o \sinh \theta)}{Z_o \cosh \theta + Z_L \sinh \theta}$$

where  $Z_i$  = input impedance of line in ohms

$Z_o$  = characteristic impedance of line

$Z_L$  = load at the end of the line

$\theta$  = electrical length of line at the frequency of interest.

For Figure 1a,  $Z_L = 70$  ohms for the short circuit case and infinity for the open circuit.

The input impedance of the 10.6-km section of the line, that is the impedance looking into the line at the 3.6-km point, is given by the above

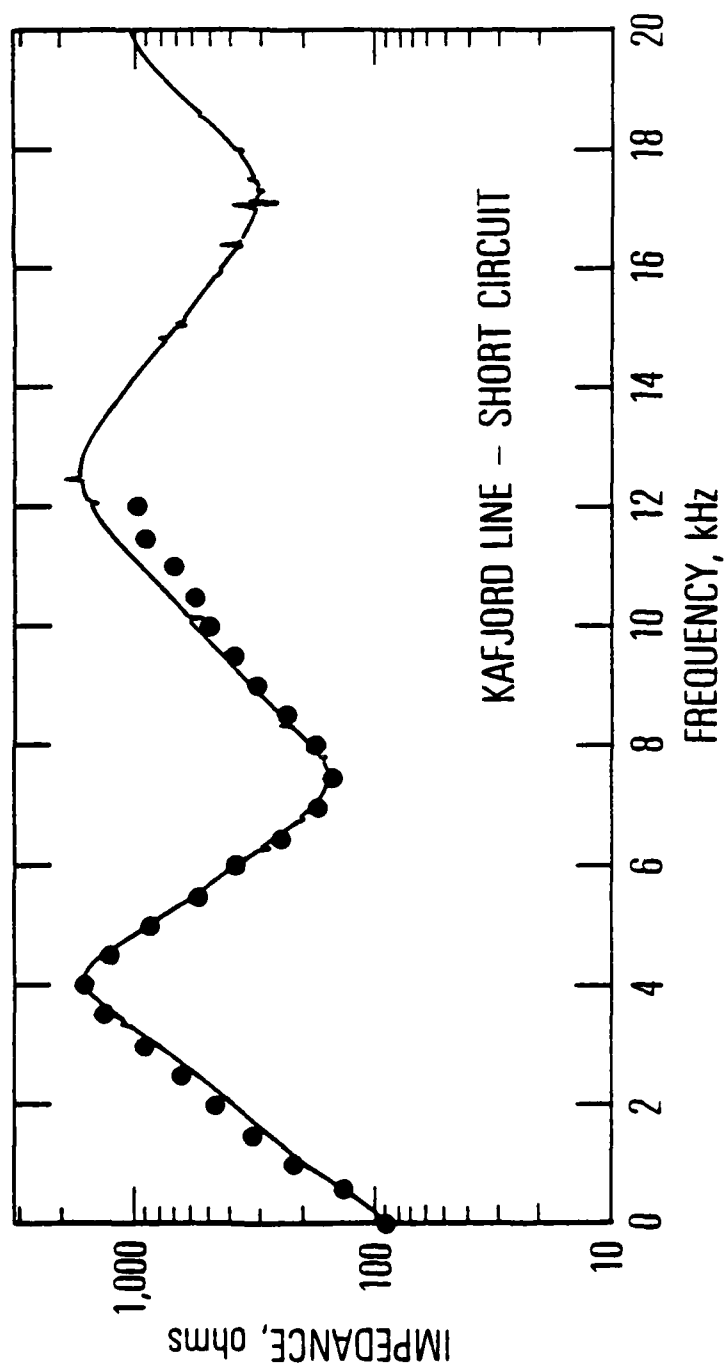


FIG. 2. Short circuit impedance of the Kafjord line.

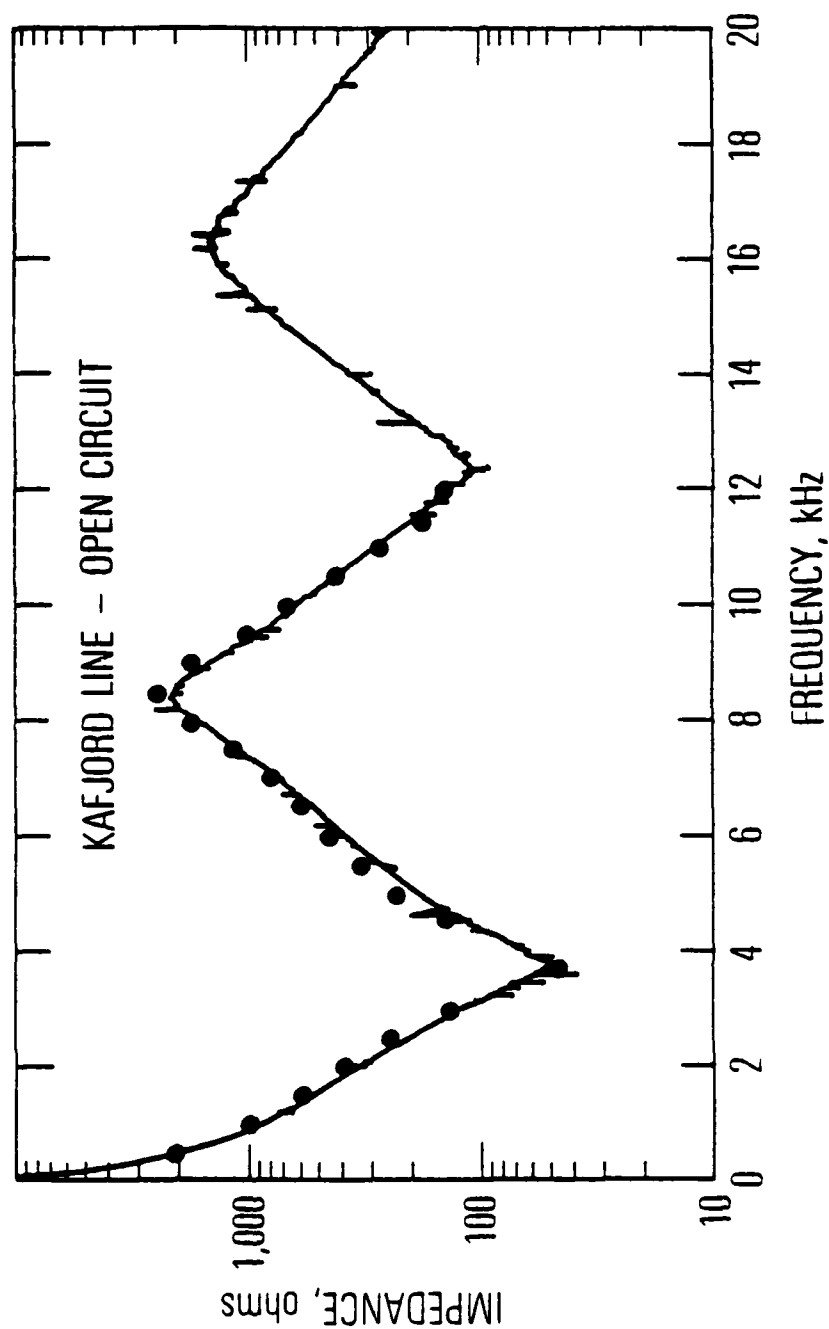


FIG. 3. Open circuit impedance of the Kafjord line.

expression with the proper loads substituted. If we call this impedance  $Z_{13.6}$ , we have a load resistance for the 3.6-km section of line given by:

$$Z_L = Z_{13.6} + 20.$$

If this  $Z_L$  is substituted into the general transmission line formula, together with the new electrical lengths and characteristic impedance, 500 ohms for the 3.6-km line, we obtain the input impedances at the transmitter end of the Kafford line. Since most of the values are complex, the input impedance is complex. Therefore the total magnitude, or modulus, must be obtained for comparison.

The transmission line expressions were programmed in a TI 59 calculator. The assumptions and procedures used for the trial and error fitting were as follows:

1. The earth resistance was assumed to be given by  $R_e/m = 10^{-6} \times f$  ohms/meter.
2. The value of the insertion resistance at the 3.6-km point was estimated from the first minimum of the open circuit impedance curve by subtracting the earth resistance.
3. The value of the insertion resistance at the short circuit, or far end of the line, was estimated from a somewhat risky extrapolation of the open circuit impedance to zero frequency, and subtracting the insertion resistance at the 3.6-km point.
4. The 3.6-km section of line was assumed, based on wire diameter and spacing, to have a constant impedance of 500 ohms and a propagation velocity of 1.0, with negligible resistance.

5. Estimates were made of  $Z_o$  and  $v_p$  in the region of 4 and 8 kHz, the frequencies of resonances and anti-resonances in the short circuit and open circuit cases. In general, the low impedances represent essentially the series resistance,  $R_s$ , of all elements, as modified by the 3.6-km section of line. The high impedance represents the value of:

$$Z_1 = \frac{Z_o^2}{R_s}$$

which is mainly dominated by the value of  $Z_o$ . The location of the minima and maxima are determined by  $v_p$ . As used in this report  $v_p$  is the propagation velocity divided by the velocity of light,  $c$ , in free space.

6. Values of  $Z_o$  and  $v_p$  were tried until good fits to the experimental curves were obtained. That is, the peaks and dips had proper magnitudes and frequencies. This was done at 4 kHz, and repeated at 8 kHz.
7. The inductance/meter,  $L/m$ , and capacitance/meter,  $C/m$ , were then determined from:

$$L/m = \frac{Z_o}{c v_p} \quad \text{Henrys/meter}$$

$$C/m = \frac{1}{c Z_o \times v_p} \quad \text{Farads/meter}$$

The results from the above assumptions and the curve fitting are shown in Table 1. The calculated values of the capacitance increased and inductance decreased with frequency, as expected, since the ground currents flow closer to the conductor as the frequency is increased. The experimental data is not sufficiently sensitive to provide the functional relationship between inductance, capacitance, and frequency, so a linear relationship was assumed.

Table 1. Kaffjord Line Impedance Parameters

<u>Parameter</u>	<u>Value</u>
Inductance/m, Henrys/meter	$2.16 \times 10^{-6} - 7.5 \times 10^{-11} \text{ f}$
Capacitance/m, Farads/meter	$1.13 \times 10^{-11} + 3.5 \times 10^{-16} \text{ f}$
Insertion Resistance at transmitter end, ohms	20
Insertion Resistance at far end, ohms	70

From L and C, we can calculate  $Z_o$  and  $v_p$  as a function of frequency, from:

$$Z_o = \sqrt{L/C}$$

and

$$v_p = 1/(c \sqrt{LC})$$

Curves showing the variation of  $Z_o$  and  $v_p$  with frequency, as calculated from the expressions above are shown in Fig. 4.

#### Capacitive Tuning of the Kafjord Line

The Kafjord line resonated at 3.8 kHz in the quarter-wave open-circuit mode. Operational requirements made it necessary to operate at 1.3 kHz, and in 1979 this frequency was obtained by adding capacitors to the far end of the line.

Simple trigonometric expressions are usually adequate for estimating the value of the capacitance required and the expected losses. Based upon earlier measurements, it was assumed that the line would have a characteristic impedance of about 350 ohms (somewhat less than the 417 ohms obtained from the results presented in Fig. 4), and a velocity of propagation of about 0.7 c.

The impedance of a short circuit line operating below its resonant frequency when measured at the open circuit end is given by:

$$Z_{oc} = j Z_o \tan \theta$$

where

$$\theta = \frac{360^\circ \times 14,200 \times 1300}{3 \times 10^8 \times .7} = 31.6^\circ$$

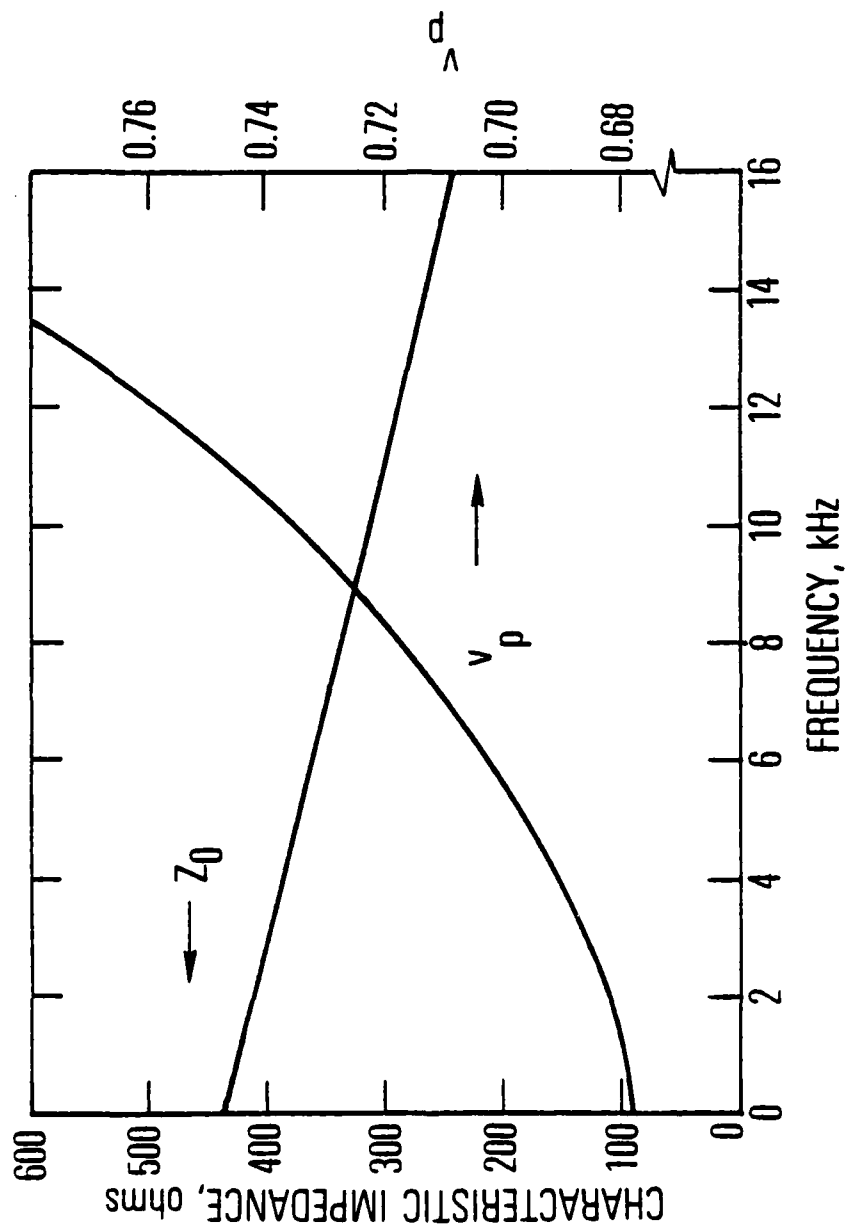


FIG. 4. Characteristic impedance  $Z_0$  and wave phase velocity  $v_p$ .

Since the above value is inductive, the line can be 'tuned' with a capacitor with the same numerical value of reactance:

$$X_C = 350 \times \tan 31.6^\circ = 215 \Omega$$

or

$$C = \frac{1}{2\pi \times 1300 \times 215} = 5.6 \times 10^{-7} \text{ farads}$$

Operating high voltage, high current capacitors at any other frequency than 60 Hz requires special considerations and most manufacturers would prefer that you not use their products in that manner. It was possible to obtain capacitors with the standard loss factor rating, a series conductor resistance rating, and a wattage rating. From the specifications it was possible to determine an array of capacitors which could be used, although not at the maximum power desired. The capacitor specifications are given in Table 2.

It was estimated that at 1.3 kHz, the total capacitor current would be 35 amperes for an input current of 40 amperes from the TVLF system. The total voltage at the capacitors would then be 8,000 volts.

Twenty capacitors were purchased and pairs were connected in series, then ten pairs were connected in parallel, so the voltage on each capacitor was divided in 1/2 and the current was divided by 10. The losses could then be calculated for each capacitor:

$$\text{Dielectric Loss} = \text{Power factor} \times \text{voltage} \times \text{current}$$

$$= .001 \times 4,000 \times 3.5 = 14 \text{ watts}$$

$$\text{Conduction Loss} = (\text{Current})^2 \times \text{conductor resistance}$$

Table 2. Capacitors Used to Tune the Kafjord

Line to 1.3 kHz

<u>Parameter</u>	<u>Value</u>
Capacitance, $\mu\text{F}$	0.1
Voltage rating, kV	13.
Power factor	0.001
Conductor resistance, ohms	0.25
Power dissipation, W	10.
Total Capacitance, $\mu\text{F}$	0.56

$$= (3.5)^2 \times 0.25 = 3 \text{ watts}$$

for a total of 17 watts. Since the capacitors were only rated for 10 watts, care was taken to operate at less than 60% duty cycle. The wattage rating is based on a 40° temperature rise. The location of the capacitors on the top of a mountain where there was a steady cold breeze would probably have allowed up to 100% duty cycle without much danger of overheating.

The equivalent series resistance of the capacitors was:

$$R = \frac{P}{I^2} = \frac{17}{3.5^2} = 1.4 \text{ ohms.}$$

The net resistance for the series-parallel array was about 0.3 ohms, which was negligible compared to the earth insertion resistance.

Figure 5 shows the impedance vs frequency curve with 0.46 uF capacitance. The minimum impedance at resonance, i.e., the total series resistance, is the parameter that determines the antenna current possible with a given amount of transmitter power. The allocation of resistance is as follows:

Insertion Resistance at 3.6 km	= 20 $\Omega$
Ground Transmission Resistance	= 14 $\Omega$
Insertion Resistance at Capacitors	= <u>50 <math>\Omega</math></u>
Total	= 84 $\Omega$

Since all the current in the line does not go through the capacitors, the apparent resistance is somewhat less than the 70 ohms determined as described in the previous section. The current which does not go through the capacitors is returned to the earth as displacement current along the length of the line.

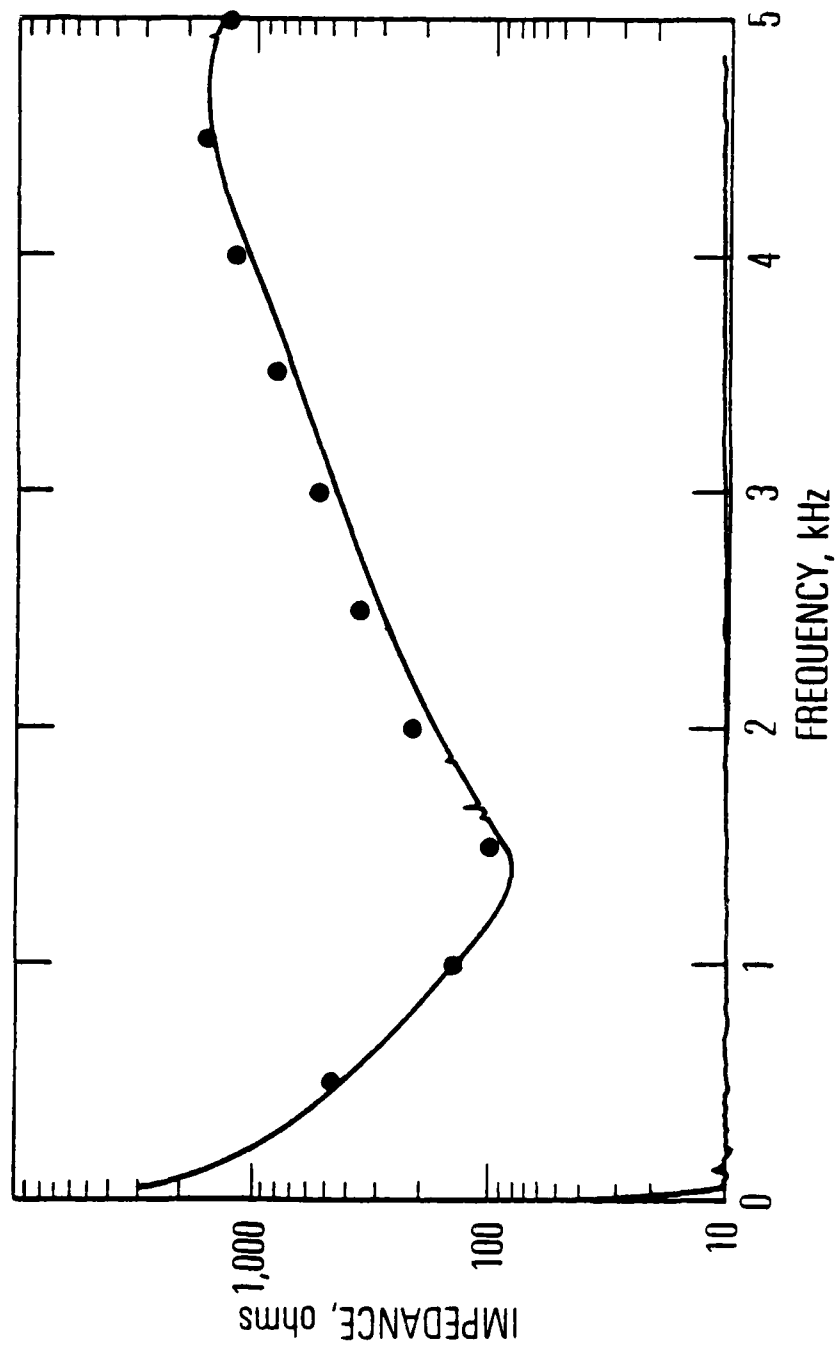


FIG. 5. Impedance of the Kafjord line tuned by 0.46  $\mu$ F capacitance in series with the line to ground at the far end of the line from the transmitter.

### Inductive Tuning of the Kafford Line

If an inductor is placed between the transmitter and the transmission line, the resonant frequency will be reduced. If we take the same frequencies as in the previous section we may determine the value for this inductance.

The impedance of an open circuit line is given by:

$$Z_1 = -Z_0 \cot \theta = -350 \cot 31.6^\circ = -569 \Omega$$

Since this is capacitative, this may be tuned by an inductance with the same reactance, and the value of the inductance is:

$$L = \frac{569}{2\pi \times 1300} = .070 \text{ Henrys}$$

Typical inductors have high losses at high frequency because the conductors are immersed in their own alternating magnetic field causing eddy currents. The large equivalent series resistance may be reduced by using an 'open' construction at the expense of increasing the length, spacing and size of the conductors. The final inductor design was based on Grover (1946) and Terman (1943). The physical and measured electrical parameters of the inductor are given in Table 3.

The measured results were within reasonable agreement with the calculated values.

A 50-foot roll of soft copper tubing was sufficient for each layer. Tubes were soft soldered using a butt joint. Spacers were glass melamine. Assemblies of 12 layers were fabricated at El Segundo and shipped by air to Tromso for final assembly of the full 120 layers at the site of the TVLF transmitter.

Table 3. Inductor Used to Tune the Kafjord Line to 1280 Hz.

<u>Parameter</u>	<u>Value</u>
Turns	600
Turns/layer	5
Outside diameter, inches	36
Height, inches	120
Horizontal turn spacing, inches	1
Layer spacing, inches	1
Conductor diameter, inches	0.25
Inductance, Henrys	0.078
Resonant bandwidth, Hertz	15.4
Q	82.8
Series Resistance, ohms	7.5

Figure 6 is a "Q" curve obtained from the inductor. Figure 7 is impedance curves of the line, the inductor, and the line with the inductor installed.

Note that the series resistance was lowered to 45 ohms with inductive tuning, as compared to 84 ohms with capacitive tuning, allowing currents as high as

$$I = \left(\frac{P}{45}\right)^{1/2} = \left(\frac{10^5}{45}\right)^{1/2} = 47 \text{ amperes for}$$

the 100-kW transmitter.

#### Skin Depth and Earth Resistivity

The skin depth of the electrical signal in the earth may be determined if the characteristic impedance and propagation velocity of a transmission line are known. Expressions that have been derived to relate the characteristic impedance of a line to the dimensions of the line, wire size, spacing, and height above ground assume a line of infinite length above a perfectly conducting plane.

For a three-wire line above a conducting ground plane, the characteristic impedance is given by

$$\begin{aligned} Z_0 = 138 e^{-1/2} & \{ [\log(4h/d) \log \{(4h/d) [1+(h/D)^2]\}^{1/2} \\ & - 2 \{ \log[1 + (2h/D)^2]^{1/2} \}^2 ] \\ & + \log \{(4h/d)^3 [1 + (2h/D)^2]^{-2} [1 + (h/D)^2]^{1/2} \} \end{aligned} \quad (1)$$

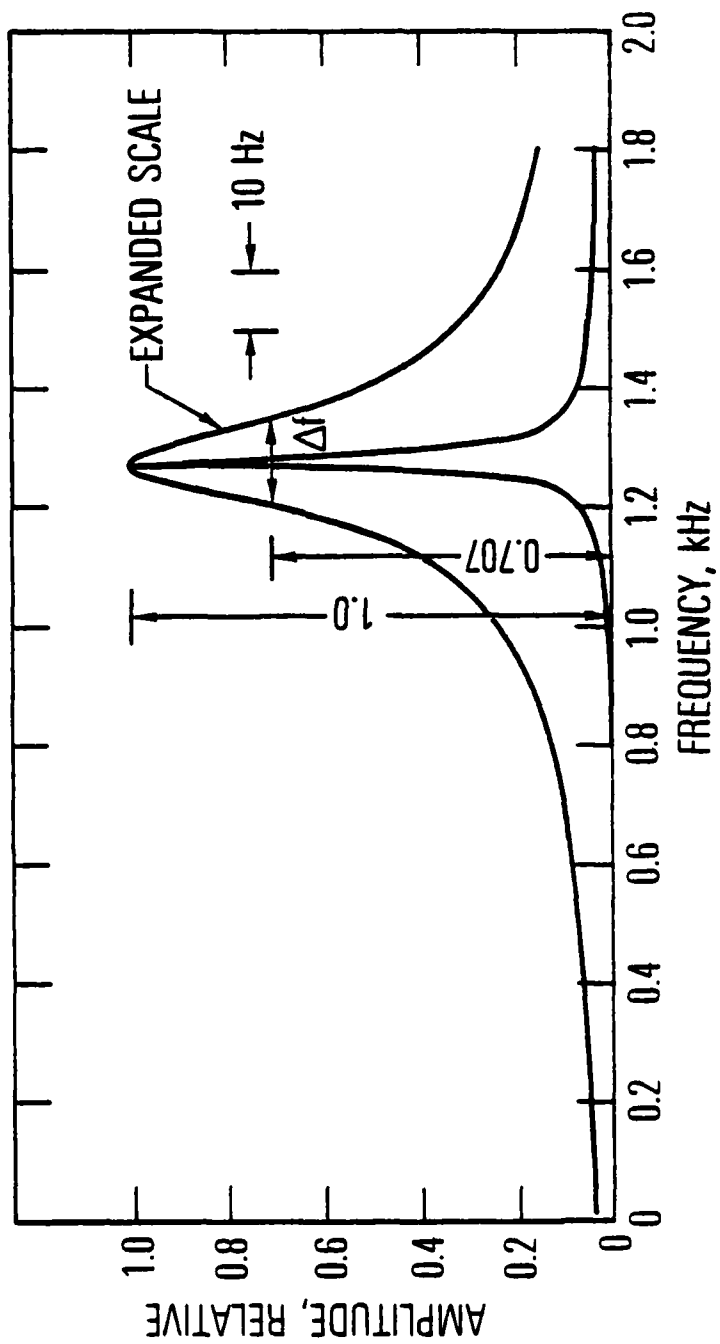


FIG. 6. "Q" curve of the Kafjord line tuned by a 70 mH inductor in series with the line at the transmitter end of the line.

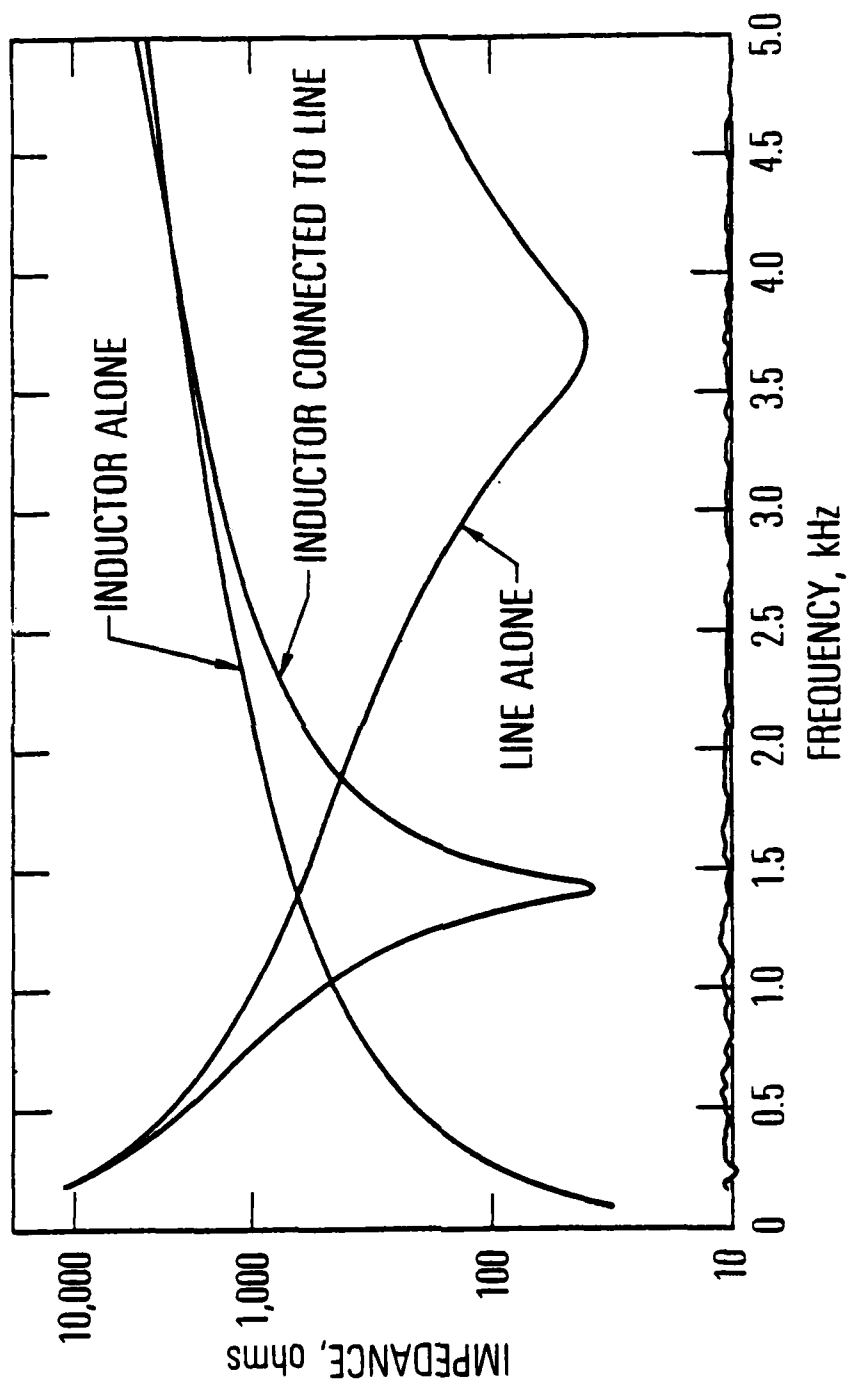


FIG. 7. Impedance of the Kafjord line in the indicated configurations.

where:

- h = height above ground plane
- d = wire diameter
- D = wire spacing
- $\epsilon$  = dielectric constant of space surrounding the wires.

For low frequencies and large skin depths in the earth, it is possible to disregard the approximately 9 meters of air between the transmission line and earth. If we use the velocity of propagation and characteristic impedance for 1280 Hertz, we can determine the effective depth of the current, h, from the above expression, since the relationship between dielectric constant and velocity is given by

$$v_p = (1/\epsilon)^{1/2}$$

The parameters used to evaluate Eq. (1) are given in Table 4. The value of h is found to be 3440 meters. The relationship between skin depth,  $\delta$ , and h is

$$h = \frac{\delta}{\sqrt{2}}$$

or  $\delta = 4860$  meters.

For a homogenous earth the value of the conductivity obtained from the equation

$$\sigma = (\delta^2 \pi f \mu_0)^{-1}$$

Table 4. Electrical Properties of the Kafjord Line at 1280 Hz.

<u>Parameter</u>	<u>Value</u>
Wire diameter, meters	0.0087
Wire spacing, meters	1.5
Characteristic impedance, ohms	417
Velocity of propagation	0.681 c
Dielectric constant	2.16

is  $8.4 \times 10^{-6}$  S/m at 1280 Hz.

Analysis of Norwegian transmission lines using this approach appears to result in values of earth conductivity considerably smaller than the normally accepted minimum values obtained elsewhere using other measurement techniques. The low values of conductivity and consequently skin depths yield larger radiated powers than would be expected. It is not practical, within the scope of this effort, to determine the cause of the discrepancies, if they exist. Some possible sources of error include earth inhomogeneity or end effects, which may be important because the apparent skin depth is the same order of magnitude as the total length of the line.

#### Radiation Resistance

The radiation resistance  $R_r$  for a power line loop antenna can be obtained from (Bernstein et al., 1974)

$$R_r = \frac{\pi^3 \times 377 \times \sigma^2 \times \ell^2}{2 \times h_1 \times \lambda^3}$$

The value obtained for the Kaffjord antenna parameters in Table 5 is  $R_r = 0.018$  ohms. For a typical operating current of 40 amperes, the radiated power,  $P_r = I^2 R_r$ , is 29 W.

Field strength measurements were made at Lanvangsdalen and Kiruna during the 1980 campaign by the University of Sheffield personnel; however, results are not yet available. These field strength measurements, made a reasonable fraction of a wavelength from the transmission line, are expected to provide data for a better estimate of radiated power in the near future.

Table 5. Parameters Used to Compute the Radiation Resistance  
of the Kaffjord Antenna at 1280 Hz.

<u>Parameter</u>	<u>Value</u>
Skin depth, meters	4,860
Line length, meters	11,600
Ionospheric height, meters	80,000
Wavelength, meters	234,000

### Accuracy

The method of determining skin depth from impedance measurements is subject to errors resulting from the accuracy of the measurements in addition to the problem of using infinite transmission line relationships for a finite length line.

The impedance plots were made automatically, and reproduce to a line width. Operational constraints prevented making the measurement over a number of days to determine if values changed as a function of climatic conditions, i.e., rain. The impedance plots are on a logarithmic scale where a 0.1 inch error is a 12% error in impedance. The characteristic impedance and the propagation velocity, from which the effective height of the conductors and the skin depth is obtained involve algebraic manipulation of the impedances which do not cause a significant increase in error.

However, the height of the conductors,  $h$ , is a sensitive function of the characteristic impedance,  $Z_0$ , and the propagation velocity,  $v_p$ . The equation for the three-wire line in terms of  $h$  appears to be intractable, however, the equation for a single-wire line as a function of  $h$ , is given by:

$$h = \frac{a}{2} (10)^{Z_0/138 v_p}$$

If the value of the exponent is the order of 1.0 a 10% error in  $Z_0$  causes about a 26% error in the value of  $h$ . If however, as is the case with the Kafford transmission line the exponent value is about 4, the error in  $h$  for a 10% error in  $Z_0$  is about a factor of 2.5.

Since the radiated power goes as the square of the skin depth, the power estimates could vary widely if there are errors in the measurement or the assumed model.

Figure 8 shows the spread of results that would occur for a 10% error in  $z_o/v_p$ .

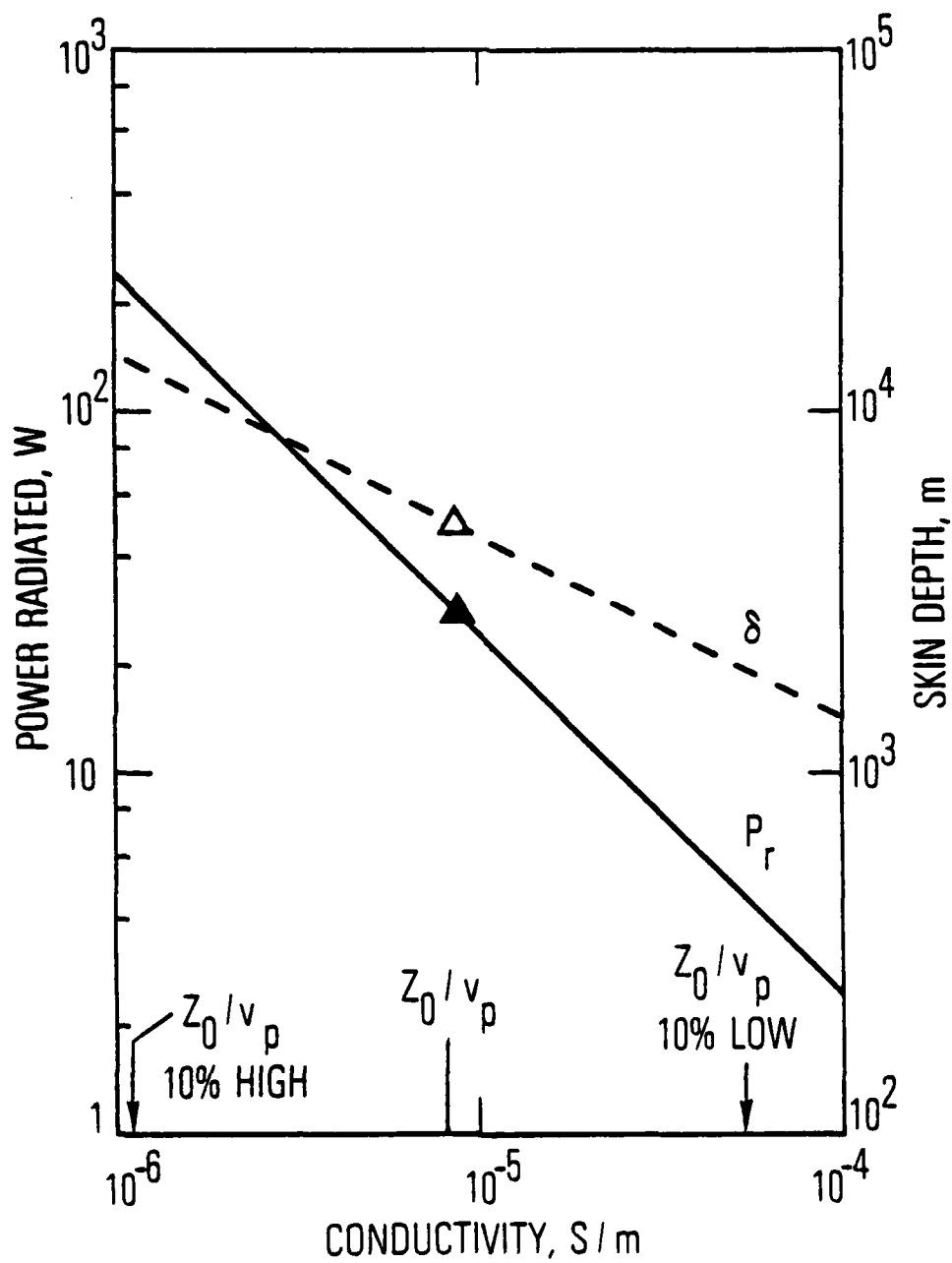


FIG. 8. Power radiated,  $P_r$ , and skin depth,  $\delta$ , at 1280 Hz as a function of rock conductivity. The triangles are the result of the measurements and calculations reported here. The conductivity for 10% errors in  $Z_0/v_p$  are also indicated.

## Conclusions

The 100-kW TVLF system was operated in Kafjord Norway (300 miles from Tromso) during the summers of 1979 and 1980, using a 14-km, 22-kV transmission line as an antenna. The results of impedance measurements on other lines provided data which allowed calculation of both capacitive and inductive tuning elements for use in lowering the frequency to a value approximating one half of the electron gyrofrequency in the vicinity of the SCATHA and GEOS satellites.

Radiated power, estimated from the measured characteristic impedance is about 29 watts for 40 amperes antenna current. An independent estimate of radiated power will be made when field strength measurements are made available.

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